U.S. DEPARTMENT OF COMMERCE
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PB-273 264

Biological Control of Aquatic Nuisances - A Review

Corvallis Environmental Research Lab, Oreg

Jul 77

EPA-600/3-77-084
July 1977

PB 273 264

Ecological Research Series

UNITED STATES · ENVIRONMENTAL PROTECTION AGENCY ·

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TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/3-77-084	2.	3. RECIPIENT'S ACCESSION NO. PB273264
4. TITLE AND SUBTITLE Biological Control of Aquatic Nuisances - A Review		5. REPORT DATE July 1977
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Gerald S. Schuytema		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Environmental Research Laboratory-Corvallis, OR Office of Research and Development U. S. Environmental Protection Agency Corvallis, OR 97330		10. PROGRAM ELEMENT NO. 1BA031
		11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS same as box 9		13. TYPE OF REPORT AND PERIOD COVERED Final
		14. SPONSORING AGENCY CODE EPA/600/02
15. SUPPLEMENTARY NOTES		

16. ABSTRACT

A total of 532 references on the biological control of aquatic nuisances were reviewed. Three major control approaches exist. Grazing and predation have been the most frequently utilized techniques, with emphasis on macrophyte control by fish and insects. The use of pathogens is potentially effective, with most promise in macrophyte control. Biomanipulation, the exploitation of the interrelationships among plants and their environment is a most promising technique for eutrophic systems. This approach includes increasing algal grazers while controlling zooplanktivores and exploiting the competitive and growth limiting reactions among various species. The importance of using host-specific organisms to prevent damage to desirable components of the ecosystem is emphasized.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Aquatic weeds*	Inhibition	Biological Control*	06/C
Reviews *	Fishes	Eutrophication*	08/H
Cyanophyta*	Insects	Biomanipulation*	
Viruses	Snails	Water hyacinth	
Fungi	Phytoplankton	Alligator weed	
Bacteria	Zooplankton	Agasicles	
Competition		Neochetina	
		White amur Tilapia	

18. DISTRIBUTION STATEMENT Release to public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 101
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE A06-A01

EPA Form 2220-1 (9-73)

★ U. S. GOVERNMENT PRINTING OFFICE: 1977—798-537/203 REGION 10

EPA-600/3-77-084
July 1977

BIOLOGICAL CONTROL OF AQUATIC NUISANCES - A REVIEW

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FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and thier impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Corvallis Environmental Research Laboratory, (CERL).

The primary mission of the Corvallis Laboratory is research on the effects of environmental pollutants on terrestrial, freshwater, and marine ecosystems; the behavior, effects and control of pollutants in lake systems; and the development of predictive models on the movement of pollutants in the biosphere.

This report reviews biological methods commonly in use or proposed to control the manifestations of excess nutrients in aquatic ecosystems. Such methodology in many cases may bring about the economical and full utilization of these nutrients to the best advantage of the environment and man.

A. F. Bartsch
Director, CERL

PREFACE

A diverse and widely based literature exists on biological control for the management of eutrophic aquatic ecosystems. Excessive nutrient input usually results in objectionable symptoms of eutrophication such as excessive macrophyte development, algal blooms, dominance of undesirable fish and nuisance insect populations. Biological manipulation in which a balanced aquatic ecosystem is maintained, may be one means of alleviating these symptoms when nutrient loading cannot be controlled.

For example, biological control (biocontrol), often utilized in agricultural and other problem areas of the terrestrial environment, has become important in aquatic weed control as a more satisfactory alternative to chemical and mechanical procedures. While biological control of macrophytes historically has focused on drainage problems and the choking of navigable waterways, it has recently received more attention as part of lake restoration measures. Control techniques in aquatic ecosystems can be divided into three general categories: grazing and predation, in which undesirable forms are controlled through the feeding activities of an introduced organism; use of pathogens, the control of undesirable plants or animals by viruses, bacteria or fungi; and biomanipulation, in which the interrelationships among the plants, animals and their environment are adjusted to obtain a desired degree of control and ecological balance. The literature has been reviewed with respect to these categories.

Over 1,000 references on biological control or related topics in the aquatic environment were located, most appearing between 1960 and 1976. A total of 532 were included in this review. English units of measurement were converted and reported in metric units.

Primary data bases and sources of literature included the following:

Water Resources Scientific Information Center
    WRSIC data base - searched October, 1974
    Selected Water Resources Abstracts - November 1974 to August, 1975

National Technical Information Service
    NTIS data base- searched December, 1974
    Government Reports Announcements - January, 1975 to August, 1975

Bibliography of Agriculture
    CAIN data base - searched December, 1974
    CAIN current awareness searches - March, 1975 to

December, 1975

Biological Abstracts
- BA data base - searched February, 1975
- BA current awareness search - March, 1975 to February, 1976
- Bioresearch Index data base - searched February, 1975

Fish and Wildlife Reference Service data base - searched February, 1975

Defense Documentation Center data base - searched November, 1974; April, 1975; June, 1975; July, 1975

Eutrophication Abstracts - No. 1 (March, 1969) to No. 47 (March-April, 1975)

Algal Abstracts - Vol. I (to 1969); Vol. II (1970-1972)

Sport Fishery Abstracts - Vol. 5 (1960) to Vol. 20 (1975)

Smithsonian Science Information Exchange, Inc. data base - Searched October, 1974; March, 1975; June, 1975; September, 1975

Institute for Scientific Information, Inc.
- Current Contents - Agriculture, Biology and Environmental Sciences - January, 1974 to September, 1975

The invaluable assistance of C.R. Jung and B.M. McCauley in searching the literature is gratefully acknowledged. Valuable criticisms were furnished by J. Shapiro, K.W. Malueg, D.P. Larsen, C.F. Powers, W.D. Sanville, and D.T. Specht. Thanks are extended also to the Smithsonian Science Institute Exchange, Inc. for permission to cite a number of Notices of Research Projects.

ABSTRACT

A total of 532 references on the biological control of aquatic nuisances were reviewed. Three major control approaches exist. Grazing and predation have been the most frequently utilized techniques, with emphasis on macrophyte control by fish and insects. The use of pathogens is potentially effective, with most promise in macrophyte control. Biomanipulation, the exploitation of the interrelationships among plants, animals and their environment, is considered a most promising technique for eutrophic systems. This approach includes increasing algal grazers while controlling zooplanktivores and exploiting the competitive and growth-limiting reactions among various species. The importance of using host-specific organisms to prevent damage to desirable components of the ecosystem is emphasized.

Work was initiated in September, 1974, and completed January, 1977.

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SECTION 1

INTRODUCTION

Biological methods have often been advocated as having great potential for effective, economic and permanent control of undesirable aquatic species (1,2) and as a desirable alternative to the use of pesticides and herbicides (3). Biological control has the advantage of continued pressure without additional applications (4), reported low cost and ease of application and minimal personnel requirements (5). Some general requirements for biological control agents include an ability of the selected species to survive and maintain themselves, an ability to reduce the problem species and a capability of co-existence with native species in their new environment (6).

The primary objective of biological control is not necessarily the elimination of a species, but its reduction to a nonnuisance level; both the introduced and the target species must become compatible parts of the ecosystem (7). Control is successful when equilibrium between the predator and prey species is reached, tending to restore the balance to that which existed prior to the appearance of the pest species (8).

Many of the principles of classical biological control have been reviewed by Sailer (9) who emphasized the stability of a diverse ecosystem. For example, species introduced for control purposes can become an integral part of the ecosystem and add to its diversity, whereas chemical control can reduce diversity by eliminating species. Biological methods integrated with chemical or mechanical control procedures often produce better results than either method used alone. Perkins (10) stated that insects used in conjuction with chemical and some form of habitat manipulation might be needed for optimal control of the water hyacinth. Crowder (11) recommended an initial removal of problem weeds by mechanical means followed by the introduction of a biological control organism. However, he emphasized that the benefits of this combination method may be temporary if the waters continue to receive nutrients.

Increased interest in aquatic biological control has been indicated by recent conferences and reviews. A 1974 Conference on Lake Protection and Management at the University of Wisconsin and a Lake Management Conference at Purdue University in 1975 dealt in part with managing aquatic environments with biological controls. A symposium at the University of Florida in 1975 on Water Quality Management through Biological Control was concerned entirely with this subject; its Proceedings are an excellent compilation of current approaches (12).

Some good earlier reviews of biological control practices and principles (7, 13, 14) have been followed recently by a review of the biological control of aquatic weeds (15), a bibliography with abstracts on biological control (16) and a review of biological control and its relationship to lake restoration (17).

SECTION 2

CONCLUSIONS

Biological control is becoming increasingly significant as a management approach to alleviate symptoms of eutrophication. However, most research has been at the laboratory pilot scale level or with relatively few well documented instances of large-scale control projects. While this type of control deals only with the symptoms of excessive nutrient loading, it appears to be the only feasible solution in many situations.

Biological control of aquatic nuisances in this country was initially concerned with macrophyte control in the southeast, where drainage and navigation were affected. More recent studies have been concerned with controls of wider application. Macrophytes are most often the problem in the southern United States, and algal blooms in the north. Obviously, no one approach will be applicable to all locations. Selected procedures that have been proposed or utilized are summarized in Table 1.

Grazing and predation have been the most frequently utilized techniques, with most emphasis on macrophyte control by fish. Many grazers and predators are not host-specific and represent potential hazards to desirable components of the ecosystem. Therefore, their use must be carefully evaluated. Some control organisms, such as insects, tend to be restricted to a particular target species and thus may be more desirable as management tools; however, climate often limits their effectiveness.

Pathogens are considered potentially effective control organisms, but have not yet been used in full-scale control projects. Most pathogens are host-specific, relieving the threat of damage to nontarget species. Most promising work has been with macrophytes; algal control is under study but has not yet been achieved outside the laboratory.

Biomanipulation, which takes advantage of biotic interactions within an ecosystem, is considered by many the most promising biological management technique for eutrophic systems. Increasing algae grazers through direct innoculation or chemical stimulation, after controlling zooplanktivores with pathogens or carnivorous fish introductions, exemplifies such an approach. Exploiting competitive and growth-limiting reactions among various species, and shifting algal populations from blue-greens to greens by chemical addition or circulation are also promising areas under study.

TABLE 1. SELECTED LIST OF PROPOSED OR ACTUAL INSTANCES OF BIOCONTROL

Problem or Project	Solution or Proposed Treatment	Location	Results or Remarks	References
I. ALGAE				
	A. GRAZING			
Anabaena blooms	Amoeba	Georgia	Under study	20, 21
Microcystis blooms	*Ochromonas dancia*	Laboratory	Under study	22, 23
Phytoplankton standing crop	Mississippi silversides (*Menidia audens*)	California	Had little impact	62; R. Brown Pers. Comm.
	Silver Carp (*Hypothalmichthys molitrix*), Thickhead (*Aristichthys nobilis*)	U.S.S.R.	Proposed	54, 56
Algal growth	Silver Carp	Israel	Inconclusive	Serruya, cited in 17
Pithophora in ponds	Israeli Carp (*Cyprinus carpio*)	Georgia, Arkansas	Recommended or reported stocking rates of 62-123/ha	39, 40, 58, 59
	Tilapia Mossambica	Alabama	Controlled at stocking rates of 2,470-4,940/ha	40
Cladophora in duckponds	Mullet (*Mugil cephalis*)	S. Carolina	Cladophora almost gone in 5 months, control remained infested	58
Filamentous algae in ponds	Swan (*Cygnus olor*)	Michigan	Stocked at rate of one pair per 0.2-0.4 ha	71, 326
	B. PATHOGENS			
Blue-green algae	Virus-cyanophages	U.S.S.R.	Reported to have lysed blue-green algal scum	Topachevsky, cited in 413
	Cyanophages	Laboratory	Suggested as controls, under study	395, 397, 411, 412
	Bacteria-*Bdellovibrio bacteriovorus*	Laboratory	Has potential, under study	431

(continued)

TABLE 1 (continued)

Problem or Project	Solution or Proposed Treatment	Location	Results or Remarks	References
	C. BIOMANIPULATION			
Nuisance algae	Alleopathic or heteroinhibiting substances	Laboratory	Substances produced by green alga Pandorina morum promising	528, 529
Large colonial algae	Zooplankton-Daphnia magna	---	Suggested as algae control after zooplanktivores reduced by carnivores	27
Phytoplankton	Zooplanktivorous fish	---	Suggested as means to allow zooplankton to increase and consume phytoplankton	27
	Pantothenic acid	---	Suggested as means to increase zooplankton	27
	Environmental manipulations	---	Additions of HCl, CO_2 or Cl_2 or other substances might help shift algal populations from blue-greens to greens. Zooplankton might be increased and algae subsequently decreased by lowering pH	27
[illegible] MACROPHYTES				
	A. GRAZING			
Overabundant vegetation in small lakes and ponds	Snails-Marsia	Florida, Puerto Rico	9,875-19,750 snails/ha eliminated submersed vegetation in 12-18 months	96, 158, 159
Water hyacinth water lettuce	Snails-Pomacea	Laboratory	About 100 snails eliminated 2,500-5000 g of plants in 29-44 days	150
Water hyacinth	Weevil-Neochetina	Florida, Texas, Louisiana	Promising control, under study	81, 82, 87, 91
	Moths-Acigonia, Arzama	South U.S.A.	Under study	87
	Mite-Orthogalumna	South U.S.A.	Promising candidate	147
	Grasshopper-Cornops	South U.S.A.	Under study	87, 113, 137

(continued)

TABLE 1 (continued)

Problem or Project	Solution or Proposed Treatment	Location	Results or Remarks	References
Alligator weed	Flea beetle-*Agasicles*	Florida	Most effective, consumed extensive areas; severe damage when 54-108 adults/m2	95, 103 104, 105
	Stemborer-*Vogtia*	N. Carolina to Florida	Very promising control	104, 105, 131
Salvinia	Moth-*Samea*, Grasshopper-*Paulina*	Africa	Results uncertain in Kariba Lake	79
Excessive vegetation	Crayfish-*Orconectes causyi*	New Mexico	Successfully cleared several lakes	169
	Crayfish-*Orconectes causyi*	S. Dakota	Control in reservoir not documented	170
	Crayfish-Pacifasticus	Washington	Results inconclusive	171
	Crayfish-Spp.	Wisconsin	Not recommended	172
Weed infested lakes and ponds	White amur (*Ctenopharyngodon idella*)	Sweden	*Myriophyllum* decreased to half the amount present in previous year in Lake Osbyjon	201, 202
	White amur (*Ctenopharyngodon idella*)	Arkansas	Amur effective in controlling weeds, generally stocked at 25 20-25 cm fish/ha; stocked in over 100 lakes	198
	White amur (*Ctenopharyngodon idella*)	Iowa	Reduced standing crop of aquatic weeds by half in Red Haw Lake	243
	White amur (*Ctenopharyngodon idella*)	Alabama	Controlled weeds in ponds	40, 61, 211
	White amur (*Ctenopharyngodon idella*)	U.S.A.	Uncertainty of effect of introduction a disadvantage. Banned in many states.	181, 185, 268, 270, 281, 282, 287

(continued)

TABLE 1 (continued)

Problem or Project	Solution or Proposed Treatment	Location	Results or Remarks	References
	White amur (*Ctenopharyngodon idella*)	U.S.S.R.	Amur at 79 kg/ha cleared 0.42 ha pond, with a July production of 16.2 metric tons/ha, in 70 days	235
Weeds in irrigation canals	*Tilapia zilli*	California	Weed density appears less	297, 301
Macrophytes in experimental ponds	*Tilapia nilotica* *Tilapia melanopleura*	Alabama	Controlled macrophytes at stocking rates of 2,470-6,765/ha	38, 40, 61
Weed control	*Tilapia*	Rhodesia	May have had detrimental effect upon biota other than plants	van der Lingen cited in 17
	Tilapia	Sudan	Disappointing results	196
Rooted aquatics	Israeli Carp	Arkansas	Controlled when stocked at 123 0.23 kg fish/ha	60, 319
Duckweeds and leafy aquatics in ponds	Swan	Michigan	One pair per 0.2-0.4 ha pond controls weeds	72, 325, 326
	Muscovy ducks (*Cairina moschata*)	Georgia, Louisiana	15-20 ducks/ha eliminated duckweeds	58, 322
Choking of lakes by coarse emergent vegetation	Nutria (*Myocaster coypu*)	Poland	Reversed development of bog lake, depleted vegetation increased fish production	328, 329, 330
Water hyacinth	Cattle grazing in canal	Guyana	Prevented spreading of mat	73
	Manatee (*Trichechus manatus*)	Guyana	Sucessfully cleared and kept clear various canals and ponds for up to 15 years	72, 330, 336
	B. PATHOGENS			
Water hyacinth	Virus stunt disease	South U.S.A.	May have control potential	426
	Fungus-*Rhizoctonia solani*	Florida	Under study	378, 455

(continued)

TABLE 1 (continued)

Problem or Project	Solution or Proposed Treatment	Location	Results or Remarks	References
	Fungus-*Acremonium zonatum*	Florida	Under study, may have potential if used in conjuction with weevils or mites	425, 461 462
	Fungus-*Alternaria eichhorniae*	India	Under study, much potential	425
	Rust-*Uredo eichhorniae*	Argentina	Under study	467, 468
Hydrilla	Fungi	South U.S.A.	Under study	467, 468
	C. BIOMANIPULATION			
Rooted aquatics	Slender spikerush (*Eleocharis acicularis*)	California	May eliminate undesirable species through competition, under study	507, 508
Excessive macrophytes	Fertilization (induced phytoplankton turbidity)	New Jersey	Objectionable growth in 18 ha lake eliminated after two-year program, boating and fishing improved	501, 502, 503
	Fertilization (induced phytoplankton turbidity)	Kansas	Vegetation controlled in 16 ha lake, total of 347 kg/ha of ammonium sulfate and 226 kg/ha of triple superphosphate used	504
III FISH				
	A. PREDATION			
Bluegills in ponds	Spotted gar (*Lepisosteous oculatus*)	Alabama	Not controlled	365
Bluegills in lakes	Northern pike (*Essox lucius*)	Nebraska	Successful control	370
Perch and Bass	Largemouth bass (*Micropterus salmoides*)	Ohio	Not controlled	366
	Muskellunge (*Essox mosquinongy*)	Wisconsin	Reduced to unmeasurable level within a year	368
Stunted panfish	Walleyes (*Stizostedion vitreum*)	Wisconsin	Ineffective	363

(continued)

TABLE 1 (continued)

Problem or Project	Solution or Proposed Treatment	Location	Results or Remarks	References
Overabundant panfish	Northern pike	Colorado	Successful at 62 15-cm fish/ha in reservoirs	371
	B. PATHOGENS			
Zooplanktivorous fish	Fish diseases	---	Proposed as means to decrease phytoplankton by increasing zooplankton	442
Tilapia	Hybridization	California	Under study as means to develop control fish which do not reproduce in wild	490
Fish	Sterilization and sex-reversal	---	Suggested to control fish populations	369, 483, 485
IV INSECTS				
	A. PREDATION			
Mosquitoes	White amur	U.S.S.R.	Proposed as control since amur consumes plants upon which insects depend	351
Chironomid midges	Carp and goldfish	California	Effectively reduces nuisance outbreaks in limited situations	354
Chaoborid midges	Mississippi silversides (*Menidia audens*)	California	Has had little impact	63, 356 R. Brown Pers. Comm.

SECTION 3

RECOMMENDATIONS

Research should continue on all biological control techniques (grazing, predatory, pathogenic and biomanipulative) as no single method is universally applicable. Some methods are more promising than others, however.

Grazing by fish has demonstrated little success in controlling algal blooms. Further research into the grazing potential of other forms, such as protozoans or zooplankton, may be more profitable. Control of the water hyacinth by Neochetina and alligator weed by Agasicles and Vogtia has demonstrated the ability of host-specific insects to control macrophytes. This type of approach, rather than the indiscriminate introduction of nonspecific fish such as the amur, is recommended as a sounder ecological practice.

Increased emphasis should be placed on the potential effects of a control organism on all nontarget segments of the ecosystem into which it is introduced. Predator or grazer species which are not host-specific and considered for control of nuisance growths and organisms should be throughly researched before introduction. These organisms may be better used in areas where their spread would be restricted by climate. Sterile species should be a primary consideration in the introduction of nonspecific organisms.

Plant pathogens seem to have much potential for controlling undesirable species, particularly because of host specificity. Although viral, bacterial, and fungal controls of algae and macrophytes are not yet fully usable techniques, they still merit investigation.

Biomanipulative procedures which exploit the interactions between the biota and their environment appear to be a most promising approach for alleviating the symptoms of eutrophication in lakes. These methods avoid for the most part, the problem of introducing nonspecific or exotic organisms into the environment. The effectiveness of decreasing algal populations by increasing zooplankton while reducing zooplanktivores has been demonstrated and is worthy of further development.

Exploitation of competition between aquatic plants may produce practical control techniques. Research should continue on the synthesis of naturally occuring growth inhibiting compounds applicable to algal control. Shifting predominant algal populations by chemical addition, while more an environmental than biological manipulation, should also receive further study.

Biological control programs should also include an evaluation of the potentially adverse effects of increased nutrient loading from proposed control organisms such as fish, fowl or mammals, or from procedures such as fertilization.

More documentation is needed from carefully controlled and properly designed laboratory and field experiments and full scale projects to fully evaluate the effectiveness and impact of various control procedures.

More documentation is needed on the economics of biological control practices.

SECTION 4

GRAZING AND PREDATION

Grazing by introduced organisms has often been suggested or used to control aquatic nuisances. For example, certain protozoans, zooplankton and fish consume algae while various insects, mites, snails, crayfish, turtles, fish, fowl and mammals consume macrophytes. The predation of fish upon undesirable insects and other fish has also been proposed or attempted as a control mechanism.

CONTROL OF ALGAE

Protozoans

Protozoans can graze upon or parasitize members of all major planktonic algal groups and a protozoan infestation is often followed by a decrease or elimination of certain algae (18). Amoebae differ in their ability to utilize algae. For instance, species of *Chlamydomonas*, *Pandorina*, *Anabaena*, *Ankistrodesmus* and *Gloeocystis* were consumed in varying degrees by four test amoebae (*Amoeba discoides*, *A. radiosa*, *Hartmannella castellani*, *Tetramitus rostratus*); however, they would not eat *Staurastrum* or *Chlorella* (19). A large amoeba associated with blooms of the blue-green alga *Anabaena planctonica* was suggested as a possible treatment for certain nuisance algae (20). Ahearn (21) observed this amoeba to control a nuisance algal bloom in 2 or 3 days and hoped to rear it in the laboratory so blooms could be seeded.

Ochromonas dancia, a chrysomonad alga, can feed upon the toxic blue-green *Microcystis aeruginosa* (22). The effectiveness of using *O. dancia* as a control organism depends upon a number of factors requiring further investigation. These are a continuing rapid rate of intracellular digestion of *M. aeruginosa*, maintenance of a high *O. dancia* concentration, the selective action of *O. dancia* and the detoxification of *M. aeruginosa* during digestion (23,24).

Zooplankton

Zooplankton stocking into reservoirs and other nutrient rich waters has been suggested as a control for undesirable algae (25, 26). While increasing zooplankton abundance may decrease phytoplankton populations, this technique is of little benefit where inedible algal species are present (27). This was the case in Clear Lake, California, where grazing zooplankton played a negligible part in planktonic blue-green algae removal, apparently because of an inability to ingest *Aphanizomenon* (28).

Although the survival of colonial species of blue-greens is often enhanced because they are less readily consumed by most grazers (29), the copepod *Thermocyclops hyalinus* from Lake George, Uganda, consumes *Microcyctis* and can assimilate about 35-50 percent of the ingested carbon (30). Rotifers have not been utilized or suggested for biological control purposes. However, *Lindia euchromatica* is apparently dependent upon the blue-green *Gloeotrichia* for food (31) and *Proales werneckii* parasitizes the filamentous green alga *Vaucheria* (32).

Research into species able to ingest blue-greens may be worthwhile, however, the successful use of zooplankton to alter algal abundance may involve manipulations of both zooplankton and fish populations. This is covered in a later section.

Fish

Tilapia--

Tilapia, fishes native to Africa, the Jordan Valley, Central and South America, South India and Ceylon (33) have been used or recommended in warm climates to control algae. Most instances of control, however, have involved very high stocking rates. Their acceptability for use in lakes is therefore limited not only by colder temperatures, but by the threat of over-population as well.

The diet of the Java tilapia (*T. mossambica*) is predominantly filamentous algae and diatoms (34); however, the latter remain relatively intact through the digestive tract (33). Prowse (36) considered this species suitable for phytoplankton control at temperatures above 13 C but emphasized the need for a predator to keep populations in check. It has cleared farm ponds in Puerto Rico of the algae *Spirogyra*, *Chara* and *Nitella* (37) and controlled *Pithophora* in the southeastern United States (38, 39). Avault (40) reported a stocking rate of 2,470- 4,940 fish/ha to control the latter alga.

The diet of the Congo tilapia (*T. melanopleura*) varies with different habitats; in Rhodesia it consumes about 64 percent macrophytes and 19 percent macroinvertebrates (34). It has controlled *Pithophora*, *Spirogyra* and *Rhizoclonium* in ponds at a stocking rate of 3,700 - 4,940 fish/ha (39, 40).

The Nile tilapia (*T. nilotica*) has controlled *Pithophora* in ponds when stocked at 1,975-4,940 fish/ha (40, 41). Pollard et al. (42) reported that it has a greater potential for nutrient removal from an Oklahoma Lake used for power plant cooling than hybrid buffalo (*Ictiobus*) or channel catfish (*Ictalurus punctatus*). The Nile tilapia, unlike other species, can digest blue-green algae (30, 43) and can assimilate 70-80 percent of the ingested carbon from *Microcystis* and *Anabaena* (44, 45).

The blue tilapia (*T. aurea*) has been stocked in Lake Kinneret, Israel, to limit algal growth; results are inconclusive (Serruya, cited in 17). It demonstrated little potential for algae control in Florida and its adaptability has made eradication unsuccessful (46).

Silver Carp--

The silver carp (Hypothalmichthys molitrix) is a rapidly growing fish of Chinese origin reaching 16 kg (47). The young change from a zooplankton to a phytoplankton diet at about 18 days (48) when 1.5-3 cm long (49, 50). The fish has been reported to avoid or to be unable to digest blue-green algae and to prefer green algae and diatoms (36, 50). Others, however, have reported assimilation of Aphanizomenon flos-aquae, Anabaena variabilis and Anabaena spiroides (51, 52).

Silver carp need a temperature of at least 10 C, preferring 22-23 C (50), but can withstand wintering in Polish carp ponds (49). Since it does not spawn easily outside its native system (36), breeding is often induced by hormone injections (47). The fish has reproduced successfully in the confined waters of a reservoir in Taiwan (53).

This species has been introduced into the U.S.S.R., Poland, Rumania, Bulgaria, Hungary, and Czechoslovakia for weed control and fish production programs (50). It has been proposed as a means to control phytoplankton in a Russian power station cooling reservior (54) and may become acclimated to the southern regions of that country (55). It has also been introduced into Lake Kinneret, Israel, to limit algal growth; however, results are inconclusive (Serruya, cited in 17). It has reduced phytoplankton in an enclosure in a Swedish lake (Carlsson, cited in 17). Introduction into a Singapore reservoir to control algae is planned (Choon and Ling, cited in 17).

Thickhead--

The thickhead (Aristichthys nobilis), native to China, has been considered for phytoplankton control in Russian irrigation and drainage systems and hydroelectric reservoirs (54, 56). This fish prefers planktonic diatoms and green algae but will utilize blue-green algae, including Microcystis. It has been introduced into the U.S.S.R., Rumania, Bulgaria, Hungary and Czechoslovakia where its main use has been as food rather than for weed control (50).

Common and Israeli Carp--

The Israeli or mirror carp is a strain of the common carp, Cyprinus carpio. While often used to prevent algal growth in fish ponds since its rooting activities increase turbidity (57), it is not primarily herbivorous and ingests only a small part of the vegetation (38). Stocking rates reported or recommended to control the green filamentous alga, Pithophora, in ponds, ranged from 62-123/ha for fish of unreported size to those 12-23 cm long (39, 40, 58, 59). Other studies recommended 224-336 kg of fish/ha for control of this alga (60).

The ability of the common carp to control Pithophora in fish ponds in the southeastern United States has been cited as justification for its introduction (61). Neither of these fish may be acceptable in lakes because of the threat of increased turbidity.

Mississippi Silversides--

The Mississippi silversides (Menidia audens) has been proposed as a control for the standing crop of phytoplankton in Clear Lake, California, while providing forage for sport fish such as white bass (62). It was also introduced into Upper and Lower Blue Lakes, California (63). Early results were apparently encouraging (64) but it is the opinion of many investigators that M. audens has had little impact on the algae in the lake system (R. Brown, pers. comm.).

Mullet--

Prowse (36) suggested that mullet (Mugil cephalis) might be used to control algal blooms in brackish lakes. This fish is important in pisciculture in Israel (65) and has sucessfully controlled Cladophora in some South Carolina duck ponds (58). It has also been stocked in Lake Kinneret, Israel, for over 12 years to help control algal growth, but results have been inconclusive (Serruya, cited in 17).

Milkfish--

The milkfish (Chanos chanos) is cultured in brackish ponds in Indonesia, the Philippines and Taiwan (66, 67) and consumes mainly filamentous blue-green algae of the Oscillatoriaceae and benthic diatoms (Schuster, cited in 68; 69). A larger milkfish in the Philippines consumes dense mats of floating filamentous green algae (70). Use of these fish for planktonic algae control is not encouraging but they may hold promise in tropical regions with filamentous algae problems.

Others--

Channel catfish (Ictalurus punctatus) can eliminate Pithophora in ponds when stocked at 2,470 fish/ha (40), but it has not been seriously considered as a control organism. The amur (Ctenopharyngodon idella) has controlled Pithophora and Hydrodictyon in bluegill ponds (71) but its primary use has been in controlling vascular plants.

Birds

Swan (Cygnus olor) have been used to control filamentous algae in fish ponds (Van Deusen, pers. comm.) and are usually stocked at the rate of one pair per 0.2-0.4 ha of water surface (72). These birds may represent an acceptable means of control in certain circumstances; however, their contribution to nutrient cycling in addition to any contribution to nutrient loading through the utilization of supplemental food sources should be considered.

The American flamingo (Phoenicopterus ruber), a native of Guyana which feeds by straining algae, has been suggested for study; however, it is likely to be of limited importance (73).

CONTROL OF MACROPHYTES

Insects and Mites

General--

Many insects used or proposed for macrophyte control in this country are native to South America where research on suitable candidates for introduction into the United States is still in progress (74). According to Coulson (75), who reviewed the U.S. Army Corps of Engineers activity in this area, field surveys are conducted 1) to locate natural enemies 2) to determine their life history and effectiveness as controls, and 3) to determine feeding specificity and food preference for the most promising candidates. Further tests in this country are usually conducted before release. The importation and interstate movement of potential control insects is regulated primarily by the Quarantine Agricultural Inspection Division of the U.S. Department of Agriculture. Work is also in progress evaluating the control potential of various insects in India (76). Some of the earlier surveys for insects and mites in Trinidad and northern South America have been summarized by Bennett (77, 78). Andres and Bennett (15) stressed that great attention is given to host specificity and the potential for damaging nontarget plants when considering insects for biological control. De Loach (79) emphasized the following research needs pertaining to insects as biological controls: determine if the parasites, predators and pathogens of native insects will attack the introduced species; determine if native plants will be attacked; document both the extent of control and monetary savings; and with careful ecological studies, determine if satisfactory control was obtained.

In the terrestrial environment, competition among forage plants, which are encouraged to grow, assists biological control agents in suppressing weeds. This competition may be minimal in the aquatic environment where relatively high concentrations of macrophytes may not be desired (15). Organisms which are less host specific than comparable ones attacking terrestrial plants have been suggested for macrophyte control if they are restricted to water and do not damage economically valuable plants (80).

Neochetina--

The weevil Neochetina, native to Argentina, Bolivia and Trinidad (81, 82) is one of the most promising insects for the biological control of the water hyacinth, (Eichhornia crassipes) (83). The biology, ecological relationships and identification of these weevils in South America has been under recent study (84, 85, 86, 87) and two introduced species, N. bruchi and N. eichhorniae, have become established at over 60 sites in Florida (Spencer, cited in 88).

N. bruchi, which will consume small quantities of other plants of the same taxonomic family (89), depends upon the water hyacinth to complete its life cycle (5). De Loach (90) concluded that this species is sufficiently host-specific to be safely introduced into the United States.

Both the larvae and the adult of N. eichhorniae feed upon the hyacinth with two generations per year under optimal conditions (81). The effectiveness of this species in Florida is being evaluated (91, 92) and populations are approaching control levels at some sites (88, 93). N. eichhorniae is also being stocked in Texas where its use will apparently be restricted to southern areas of the state because of temperature limitations (94). Benefits derived from the successful control of water hyacinth by N. eichhorniae would include the opening of large water areas for recreation, more efficient water distribution and flood control, a reduction in mosquito population and reduction or elimination of chemical and mechanical weed controls (8).

Agasicles--

The flea beetle (Agasicles hygrophila) appears to be the most effective insect introduced for the control of alligator weed (Alternanthera philoxeroides) in the United States (95). Feeding and egg laying are related to chemical stimulants produced by the plants (96). Both the adults and larvae feed upon the plant and thus suppress its growth by inhibiting photosynthesis. The life cycle is about 25 days, with 5 generations per year in the vicinity of Buenos Aires (97). Studies have been initiated to determine if peak beetle density coincides with minimum plant carbohydrate reserves (98).

The flea beetle was first introduced into the United States in the Savannah Wildlife Refuge, Georgia, in 1964 (99, 100, 101). Introduction into California the same year was not successful (100). The first introduction into Texas was in 1967 (102) with later introduction into other Texas areas (94). A. hygrophila was successfully released and established in Florida in 1965 (103). Since that time alligator weed has decreased with increases of the insect (104, 105). The flea beetle is now found from South Carolina to Florida and Alabama to Texas (106). Introduction of A. hygrophila into India for testing has also been suggested (107).

The flea beetle has destroyed extensive areas of alligator weed in several Texas areas (108, 109, 110) and along the Peace River in Florida (111). The latter state has been the site of its greatest success, probably due in part to its ability to overwinter here. However, the insect has not been uniformly effective in all areas of the southeastern United States, perhaps because variations in plant growth or nutrition have altered the alligator weed's attractiveness (112). Damage to the alligator weed is not noticeable when beetle density is less than about 43-54/m^2 of level area (106, 113). Severe damage has been reported at adult population levels of 54-108/m^2 (95).

The most important limiting factor in using the flea beetle for biological control is climate; the organism is sensitive to cold temperatures. Frost prevents regrowth of the plant but also severely limits populations of Agasicles, thus an insufficient number of insects are present when the plant is most susceptible (109, 110). The number of overwintering adults determines whether population densities are sufficiently high for effective control (106), since most control of alligator weed is achieved in spring (85). A new stock of beetles collected south of Buenos Aires may be better able to withstand winter in the cooler climates than those from previous releases (114).

The flea beetle is effective in consuming alligator weed treated with herbicides (115) and actually prefers young regrowth (116). Added control has thus been achieved by using the beetle in conjunction with applications of 2, 4-D (117, 118, 119). Herbicidal treatment followed by the release of 25-50 beetles/ha was more effective than using overwintering beetles alone (120). This integrated approach to aquatic weed control has been stressed by the Corps of Engineers (121) and others (95) and is also under study as a means to control water hyacinth (122).

Alligator weed, as it is suppressed by the flea beetle, becomes less able to compete with the water hyacinth and in some areas is being replaced by it (97, 106, 123).

Other Coleopterans--

Several other coleopterans (beetles) may have biological control potential. *Bagous lutulosus* appears to be specific in attacking hydrilla (*Hydrilla verticillata*) in Pakistan (124). Three curculinonids and a gelechiid, also from Pakistan, have been suggested as possible controls of watermilfoil (*Myriophyllum* spp.) (125). *Galerucella nymphaeae* may be able to limit the growth of water lilies in Russia (*Nymphaea candida*, *Nuphar luteum*) (126). The weevil *Neohydronomus pulchellus* is a promising candidate for introduction into the United States for control of water lettuce (*Pistia stratiotes*) (127). *Litodactylus leucogaster* has the potential for reducing seed production in Eurasian watermilfoil (*Myriophyllum spicatum*) (128, 129).

Vogtia--

The alligator weed stem borer (*Vogtia malloi*) was introduced into the United States from Argentina in 1971 and has become established at several locations from North Carolina to Florida (104, 105, 130). This moth promises to be one of the most widespread biological control mechanisms of alligator weed (105). It is presently important in its control in South Carolina (131) and is the subject of continuing study in Florida (114), where it has demonstrated its effectiveness by reducing the number of aerial stems from 565 to 43/m^2 in four generations (130). In Argentina, it produces three to four generations per year (132).

V. malloi may be effective in more northern areas where the alligator weed flea beetle cannot overwinter and so will supplement the biological control of this weed (123). It is able to complete its life cycle only on alligator weed. The larvae burrow into the plant immediately after the egg hatches. Early larvae are confined mostly to the stem cavity while older larvae become roving stem borers. They pupate within the stem and emerge through pre-cut windows (110, 132).

Acigonia--

The moth *Acigonia infusella* is the subject of a number of feasibility studies in Florida (88, 131) and is under consideration for introduction into the United States for water hyacinth control (93). Since this insect can also complete its life cycle on pickerel weed (*Pontederia lanceolata*) (75), its release has been delayed (133). In the hyacinth, the eggs are laid in leaf crevices and the larvae bore into the petiole; the adult emerges from an opening cut in the plant prior to pupation (88).

Arzama--

A native moth, *Arzama densa*, is also under investigation as a water hyacinth control (114). The young larvae feed upon tender parts of the hyacinth and bore into the plant as they grow older (88, 134, 135). Damage caused by this insect may be extensive; over 70 percent of the water hyacinths covering a small pond were affected within four months after the pond was innoculated with 30 larvae/m^2 (88) While *A. densa* is a potential biological control agent, it has not yet been effective in the natural environment, perhaps because of parasites (136, 137). Habeck (138) warned that the moth should not be introduced into countries where dasheen (*Calococisia esculentais*) is grown as a root crop because of dangers of infestation.

Parapoynx--

Parapoynx stratiota, a Yugoslavian moth, has demonstrated potential in the control of Eurasian watermilfoil (128, 139). Only the adult stage is spent above the water surface (140) and one caterpillar can eliminate 8-12 50 cm plants (141). *P. allionealis*, a closely related species, is also under study (140).

Other Lepidopterans--

A number of other lepidopterans have been tried or proposed as biological controls. *Epipagis albiguttalis* attacks water hyacinth in South America and may be introduced into the United States after adequate testing (131, 133). *Samea multipicalis* has been introduced into Kariba Lake, Africa, from Trinidad for control of *Salvinia* spp. but the results are unknown (79). This species also attacks water lettuce (142). The moth *Erastroides curvifuscia* has been studied in India, where in prelimimary tests, 17-86 larvae/m^2 cleared 1,230-1,340 g of water lettuce in 30-40 days (143). *Nymphula* caterpillars have been suggested for coontail (*Ceratophyllum demersum*) control in New Zealand (144) and the leaf miner *Hydrellia* appears to be specific in attacking *Hydrilla* in Pakistan (124).

Cornops--

Cornops aquaticum, a grasshopper native to South America has been studied as a possible control for water hyacinth in the United States (88, 133, 137). *C. longicorne* has also been considered (136, 145); however, some investigators believe it might be detrimental to other plants (75, 89).

Paulina--

The grasshopper *Paulina accuminata* was introduced into Kariba Lake, Africa, from Trinidad to control *Salvinia*; however, results were uncertain. This insect was also suggested as a possible control of water lettuce in the United States (80).

Thrips--

A species of thrips, (*Amynothrips andersoni*), an important suppressant of alligator weed in South America (146), was introduced into the United States in 1967 (104, 105). This insect creates lesions which cause the leaves to distort and become stunted (110). Population densities of thrips sufficient to control alligator weed have not yet developed, possibly due to predator pressure and lack of a rapid natural dispersal method; a greater impact on alligator weed is expected as populations increase (103).

Mites--

The mite Orthogalumna terrebrantis is a promising candidate for the control of the water hyacinth (147). Studies are continuing on this form (88, 89, 137) which has both North and South American varieties (75, 145). Recent studies have indicated little difference between these populations (148). The adults do not penetrate unbroken water hyacinth epidermis, whereas the immature stages can feed freely (147) and severely damage the plant by epidermal stripping (137). Serious damage to water hyacinth in Argentina has occurred at population levels sufficient to form approximately 10,000 mite feeding galleries per plant (148).

Snails

Pomacea--

The snail Pomacea australis, about 5 cm in diameter and weighing up to 27 g, is widely distributed in Brazil and has shown promise in controlling a variety of floating and submerged weeds (14, 37, 149). Ninety-three snails, weighing about 7 g each, reduced 5,000 g of water hyacinth to 260 g in 43 days, while 95 snails weighing about 2-4 g consumed 2,500 g of water lettuce in 29 days (150). Rushing has urged an investigation of P. australis as a biological control agent of water hyacinth (151), and feasibility studies are in progress in Puerto Rico (152).

Marsia--

Marsia cornuarietis, a snail native to the Magdalena and Orinoco watersheds of South America was discovered in the United States in 1957. The adults may reach a length of over 6 cm and are very hardy (96). It has eliminated submerged weeds in ponds in the southern United States and Puerto Rico (14) and has been reviewed as a candidate biological control agent (150). M. cornuarietis consumes a variety of aquatic macrophytes, and also inhibits the growth of water hyacinth by root-pruning (149, 153, 154, 155, 156).

Ponds containing 1,814 - 4,536 kg of ornamental lilies (Nymphaea ampla) and 473-7,570 m^3 of water were cleared of foliage in 51-75 weeks after the introduction of 200 M. cornuarietis each (157). On a larger scale, some small ponds and lakes in Florida stocked with the snails at the rate of 9,875-19,750/ha were free of submerged weeds in 12 to 18 months (96, 158, 159). A high stocking rate was considered necessary (156) and 80,000 adult M. cornuarietis/ha (155) were recommended for dense macrophyte infestations (155). The need for mass production of these snails was emphasized (160) and some mass rearing techniques have been developed (161). M. cornuarietis is also an efficient predator upon various snails which are vectors for schistosomiasis and liver flukes (162).

The snail cannot survive below 6 C; 10 C is the lowest temperature at which it can be expected to operate as an effective control (14, 155). This might preclude its use in the United States (4). Partington (163, 164) cautioned that this snail must not compete with certain native species or eliminate desirable vegetation.

Others--

Other instances involving snails have included experiments with the Family Pilidae in East Pakistan (165), and the suggestion that Limnaea stagnalis might control the submersed macrophyte Lagarosiphon in New Zealand (144). Rushing (150) recommended an exhaustive search for snails which would be even more species specific than Pomacea and Marsia and emphasized that snails are potentially important in an integrated aquatic plant control program.

Crayfish

Reduced littoral vegetation is often associated with dense crayfish populations (166, 167, 168). Dean (169) suggested control of aquatic vegetation by crayfish after Orconectes causeyi sucessfully cleared several lakes in New Mexico of species of pondweed (Potomogeton), coontail, elodea (Elodea), water buttercup (Ranunculus) and watermilfoil (169). Smartweed (Polygonum), bulrush (Scirpus) and cattails (Typha) were not controlled. He emphasized that crayfish desired for control purposes should be primarily vegetarian, small to moderate in size, prolific and nonburrowing.

O. causeyi was introduced into a 13 ha reservoir in South Dakota; reproduction occurred but vegetation control was not documented (170). Pacifasticus leniusculus was imported from Oregon to help clear vegetation choked irrigation return ditches in Washington. Results were inconclusive because of human predation and escapement, but research may continue (171; Hesser, pers. comm.).

Magnuson et al., (172) indicated that while crayfish control nuisance plants in some situations, they also prey upon fish eggs, reduce benthic macroinvertebrates important as fish food, provide only a marginal food for higher trophic level organisms and can eliminate native crayfish. They also emphasized that once introduced, crayfish can be eliminated only with considerable effort. Rickett (168) warned of the possibility of excessive vegetation elimination in lakes or ponds by uncontrolled crayfish populations.

Turtles

Yount and Crossman's (173) studies suggest the possibility of training turtles to eat water hyacinth. The Florida turtle, Pseudemys floridana peninsularis normally eats only unhealthy hyacinths; however, turtles which were preconditioned by eating crushed plants would eventually consume healthy plants. Two of these animals consumed 23 kg of crushed and uncrushed water hyacinths in 6 days.

Turtles have been used in aquatic weed control experiments in East Pakistan (165), and the National Science Research Council of Guyana (73) suggested that an economic incentive for cultivating certain South American turtles for weed control might effect their declassification as endangered species.

Fish

Amur--

General--The potential success of the white amur or grass carp (Ctenopharyngodon idella) for biological control of aquatic weeds has often been emphasized (174, 175, 176, 177). Nair (178) compiled a bibliography of 243 references from 1934 to 1968 on its culture and application. Reviews and evaluations of its biological control potential have been presented by Cagni, Sutton and Blackburn (179), Bailey (180), Michewicz, Sutton and Blackburn (175) and Greenfield (181). Major research programs on the amur in the United States have been conducted in Alabama by Auburn University, in Florida by the U.S. Department of Agriculture and the University of Florida, and in Georgia by the U.S. Department of Interior and the University of Georgia (182).

The range of the amur extends from 23° to 50° N (183); it is native to rivers entering the western Pacific from China, and has been introduced into the United States, Malaysia, Formosa, India, Japan, western Europe, eastern Europe and the U.S.S.R. (184). The fish is now reported in 44 of 50 states in the U.S.A. (Kennamer, cited in 185).

To spawn in its native China, the amur needs a sudden rise in water level (exceeding 1.2 m in 12 hours), a flow of approximately 60-100 m/min, and a water temperature of 26-30 C (186). Little water movement is needed for the successful hatching of eggs provided they remain suspended for 40 minutes after fertilization (183).

The growth rate of the amur is exceeded by few other fish (187) and ranges from 2.8 g/day in northern latitudes to 8-10 g/day in the equatorial regions (188). Maximum size exceeds 30 kg and 1.0 m in length (189).

The upper lethal temperature is approximately 37-39 C and overwintering can occur at 1-2 C (189). Low oxygen tensions can be tolerated (190) but feeding ceases at 2.5 mg/l, decreasing their value as a control at lower oxygen levels (191).

The amur is a popular food fish in Japan (192) and it is considered among the most important fish cultivated in Asia (193). It is also grown for food in eastern Europe (50, 194) and the U.S.S.R. (56). While its food value is often a secondary benefit in weed control projects (195, 196) consideration should be given the possibility of eating fish which have ingested weeds containing toxic substances such as arsenic (197).

Stocking the amur has changed the natural habitat in some Arkansas lakes resulting in replacement of the redear sunfish (Lepomis microlophus) and chain pickerel (Esox niger) by largemouth bass (Micropterus salmoides), bluegill (Leopomis macrochirus) and the gizzard shad (Dorosoma cepedianum) (198). While the amur usually does not appear to compete with game fish for food (199), its ability to consume common invertebrates has been demonstrated (200). There were no significant changes in the phytoplankton after amur were introduced into Lake Öbsyjön, Sweden. However, ciliates decreased in the zooplankton and there was a tendency toward more cleanwater associated organisms in the benthos (201, 202).

Feeding, diet and assimilation--The specialized pharyngeal teeth of the amur allow small specimens to exploit soft vegetation while large fish can utilize tough, fibrous material (203). They feed at intervals of only 5-7 days at 3-6 C, and more intensively above 16 C; food selectivity increases a[illegible] lower temperatures (204). A greater variety of plants is consumed as the temperature increases, and the fish grow larger (48, 205).

The literature contains numerous reports of food preferences. Although these plants vary according to location or specific feeding trial, common cattails (*Typha latifolia*) and water hyacinth are frequently avoided (206, 207, 208). The amur has been considered a feeding "opportunist" (209) and in some cases may prefer the filamentous algae *Cladophora* and *Spirogyra* to aquatic vascular plants (210). Avault, Smitherman and Shell (61) listed the preference in descending order for twelve plant species in Alabama ponds as follows:
Chara (*Chara*), Southern naiad (*Najas guadalupensis*), pondweed (*Potamogeton diversifolius*), slender spikerush (*Eleocharis acicularis*), coontail, water hyssop (*Bacopa rotundifolia*), elodea, Eurasian watermilfoil, vallisneria (*Vallisneria americana*), water hyacinth, parrot feather (*Myriophyllum brasiliense*) and alligator weed. Other preferences from the United States have been listed for Alabama (211), Florida (212, 213) and Oregon (214).

Feeding preferences have also been reported from India (207, 215, 216), New Zealand (197, 205), Poland (206), Czechoslovakia (208) and the U.S.S.R. (217, 218). Preferences from other localities have been listed by Cross (219). Krupauer (220) found over 73 species of aquatic plants in Czechoslovakia were readily eaten by the amur and Bailey (198) reported that they effectively controlled 22 species in Arkansas lakes.

The amur consumes phytoplankton and Infusoria during the first 2-4 days of life, changing to zooplankton after 5 days (221, 222). Preferences include *Daphnia*, *Polyphemus*, *Bosmina* and *Scapholebris*; *Copepoda*, *Chydorus* and *Ceriodaphnia* are shunned (48). The fish do not become phytophagous until they are about one month old and 2.5-4 cm in length (47, 49, 186).

Edwards (200) found that in aquaria, 7 to 11 month old amur would eat common invertebrates and trout fry in the presence of palatable plants when there was no cover for the prey. While the degree of predation in nature could not be predicted from these experiments, the need for additional study before introduction into trout spawning waters was emphasized.

The gut of the amur is only about one-fifth the length normally found in a herbivore (223). Food passes through the fish in less than eight hours at 28-30 C, with approximately only half of the plant material being utilized (203). Although digestion is not efficient, half of its food is sufficient for growth. Essential proteins are obtained from growing shoots, filamentous algae or animals (224).

The amur exhibits a negative nitrogen balance when fed elodea, suggesting a necessity for a food with a higher protein content, or for supplemental protein, for normal growth (191, 225, 226). A Chinese study on digestibility concluded that animal materials and the plant Wolffia arrhiza are the most suitable food of the amur once it reaches the vegetation consuming stage (227). It increases nutrient cycling by excreting 50-75 percent of the ingested phosphorus and 90-95 percent of the nitrogen (225).

Protein and caloric differences in aquatic plants result in contrasting conversions of plant material into fish flesh; while 48 g (fresh weight) of hydrilla were required for a 1.0 g weight gain, only 22 g of duckweed were required for the same increase (115). Amur similarly gained less weight on a diet of water hyacinth than on hydrilla and southern naiad (228).

Stocking rates--Most stocking rates reported are for ponds and indicate a variety of combinations of numbers, lengths, weights, and age per unit area. Blackburn (229) emphasized dependence of stocking rates on the relationships between fish size and amount and type of vegetation rather than on a standard rate. The size of the fish available, how long control is desired and the relative palatability of the aquatic weeds present are also important considerations (230).

Pond stocking rates in the United States for amur of unreported size have ranged from 49 to 99 fish/ha (40, 199, 231). Fish 15-40 cm long have been stocked at 49-1690/ha in ponds and pools (61, 211, 232). Amur weighing 0.9 kg have been stocked at 247 fish/ha (60).

Stocking rates used or recommended in Russia ranged from 36-86 fish/ha (233), to 400-500 fingerlings or two-year olds/ha (234). Seventy-nine kg/ha of one-year fish have cleared ponds of vegetation (235) and 254 kg/ha were used in canals (236). Recommended rates in Czechoslovakian ponds ranged from 2,000 one-year fish to 150 four-year fish/ha (50, 237, 238). Effective stocking rates in India ranged from 654 to 5,200/ha for fish initially weighing 62-2,640 g (215). Rates for English ponds have been reported at 92-300 kg/ha (239, 240). One hundred twenty-five to 250 kg/ha of two-year fish were also suggested as sufficient to reduce aquatic weeds by half (241).

Stocking rates reported for control of specific weeds are variable. Hydrilla and southern naiad were controlled by 309 amur/ha (115); rates greater than 49/ha were recommended for heavy hydrilla infestations (229). Water hyacinth might be controlled by 99 amur/ha if assisted by a winterkill and herbicides (176). Naiad and duckweed were controlled at a stocking rate of 136 fingerlings/ha, but not at 69/ha (191).

Use in United States--The State of Arkansas has actively used the amur in a program of aquatic weed control and has recommended its use from ecological, fisheries and economic standpoints (174, 180, 242).
Bailey (198) recently summarized its use there, where more than 100 lakes totaling over 20,250 ha have been stocked with 308,000 amur. The fish effectively controls 22 genera of aquatic macrophytes but is ineffective

against tough emergent plants. Fish culture ponds are routinely cleared of aquatic weeds by stocking amur fingerlings at a rate of 247-1,235/ha. Lakes are generally stocked at the rate of twenty-five 20-25 cm fish/ha, resulting in approximately 112 kg of fish/ha by mid-summer, sufficient for control during that year.

The amur was stocked in a 29 ha Iowa lake to evaluate its effectiveness in weed control (243). Fish averaging 31 cm and 380 g were stocked at a rate of 18/ha. They consumed 37 metric tons of vegetation, halving the standing crop of weeds by the latter part of the summer.

The Tennessee Valley Authority has initiated a multidisciplinary study on the amur in the Tennessee Valley (185). Shleser and Yeo (244) are developing sterile amur in California for weed control and are determining feeding habits, behavior and stocking rates. Evaluation of the amur as a weed control agent in Puerto Rico is presently being carried out by Benn and Rushing (245); Lembi (pers. comm.) is presently conducting field studies with the amur in fish hatchery ponds in Indiana.

Use in foreign countries--The amur has been successfully used to control weeds in Lake Obsyjön, Sweden (201, 202, 246, 247). The 4.6 ha lake was covered with Eurasian water milfoil; dry weight in 1969 was 16 metric tons. Two hundred-fifty amur averaging 380 g were introduced in May, 1970; after 100 days, the average fish weight was 1,030 g and only 7.3 metric tons (dry weight) of milfoil remained. The average weight of the amur after ice-out in 1971 was 766 g.

Acclimatization of the amur in the U.S.S.R. started in the 1930's (248) and it has since been used to reduce aquatic plants in coolant reservoirs (249). Fifty to 100/ha were sufficient to clear one reservoir of weeds; no reinfestation had occurred after seven years (250). In Turkmenia, 375 amur (total weight 55 kg) cleared 22 metric tons of milfoil from a 1.8 ha area in 110 days (251). Amur introduced into Czechoslovakian irrigation canals have eliminated the vegetation (17).

Seventeen kg of amur in an English pond increased to 173 kg in 20 weeks while consuming about 6,804 kg of weeds (252). This fish has also been used in London water reservoirs (Anon., cited in 37) and has been introduced into New Zealand (205; Chapman, White, cited in 17).

The amur has long been used to control weeds in China (Lin, cited in 253) and Japan (Araki, cited in 61). It has been imported for weed control in Pakistan (254), India (Avault, cited in 14), Malaysia (251) and Mexico (255). Its introduction into Sudan is planned to control macrophytes and the snail host of bilharzia (schistosomiasis) (196). It was also recommended as a potential biological control and an additional food source in the Chambal River irrigation system in India (195) and proposed as a control in irrigation systems in the U.S.S.R. (54, 56). Introductions are planned in Lake Carriazo, Puerto Rico (Goitia, cited in 17). The problems associated with production of amur in cold climates will be investigated in Sweden (256).

Spawning considerations--Since the amur does not often spawn outside of its native area, spawning must be frequently induced artifically in other locales. Successful spawning has been achieved in Arkansas under artificial conditions using human chorionic gonadotropin (257). Hickling (258) reviewed and summarized this procedure.

Ware et al. (46) recommended that future programs involving amur should include only sterile or monosex fish. The production of monosex cultures of amur would insure that the fish could not breed in nature and would alleviate some of the problems of exotic species introduction. However, gynogenesis, a method of producing monosex fish by fertilization with genetically inactivated sperm (259, 260) was determined impractical for mass production (261).

Bailey (180) considered the danger of spawning in the United States to be slight since the amur normally spawns in nature in a strong current after a rapid water rise (180). Widespread introduction in this country however, would eventually place it in suitable spawning locations (262). The fishes jumping ablity could lead to its spread from farm ponds into waters where its establishment is not desired (263). Amur are collected occasionally from the Mississippi River, presumably escapees from Arkansas (264); similarly, escaped fish also are found in the rivers of East and Central Europe (Holcik, Holcik and Par, cited in 265).

The Columbia River drainage system might provide conditions suitable for spawning with the subsequent danger of natural vegetation reduction in waterfowl habitats (266, 267). Spawning conditions might also be satisfied in some Missouri streams (268) and the fish could eventually become established throughout the Mississippi River Basin (269). The amur was not recommended for introduction into California because the possibility of its establishment in some of the larger rivers would be detrimental to native game fish (270, 271). In Florida, the fish might also spawn in some rivers used by the native striped bass (Morone saxatilis), and could possibly harm the sport fish production potential of the littoral zone in lakes (46). Alabaster and Scott (272) believed the amur had the potential to breed in Great Britain in some of the faster flowing rivers receiving heated effluents, and perhaps in some sluggish rivers in southwest England.

Although spawning is often believed restricted to native areas, natural reproduction has occurred in other regions. The amur has spawned in the Tone River in Japan since 1947 (273). Spawning has been reported from a fish pond in the Ukraine (Prikhodko and Nosal, cited in 272). It has also reproduced in a 360 ha reservoir in Taiwan where it had become established after fingerlings escaped from a nearby pond (53). Natural reproduction has taken place in a river and lake system in Mexico after the fish were released following water hyacinth control experiments (274, 275).

Control of the amur--Toxicants could be used to control the amur as it is about as sensitive to those materials as the common carp (276). Antimycin applied at 6 mg/l and rotenone applied at 2 mg/l killed all the amur in experimental ponds within 16 days (277). The amur is sensitive to 0.006 ppm of rotenone and might be stunned by this concentration enabling its transfer to other water bodies with minimum injury (278).

Advantages as a control--The advantages of the amur as a biological control agent are that it is primarily herbivorous and ingests significant amounts of aquatic weeds, has a rapid growth rate, is edible, has potential as a sport fish, tolerates a wide range of temperature and water quality, is susceptible to normally used fish toxicants and is economical as a control agent (185).

Disadvantages as a control--Disadvantages include: uncertainty of the effect on native fish; possibility that removal of plants may eliminate endemic fish food and cover and waterfowl food; lack of knowledge of proper stocking rates; difficulty of live capture; possibility of natural spawning; possibility of introducing a disease vector; lack of knowledge of local plant preferences; and nutrients released into the water by excretion may lead to increased primary productivity (181, 185,268).

The amur increases the production of other fish species when they are grown together in commercial ponds (241, 279), the passage of partially digested food from its gut results in a fertilizing effect which enhances algal productivity and the subsequent growth of other fish (174). Prowse (36) reported that the amur elevates the nutrient level of the water to a point where algal blooms result; Stanley (225) and Mitzner (243) also suggest this possibility. However, this effect was not noted in some soft water acidic ponds in Georgia (280).

Since the amur can survive in brackish water (281, 282), there is a possibility that it could migrate from one river system to another through estuaries. For this reason the amur might have a profound effect in the Sacramento - San Joaquin Delta of California should it become established in that state (270).

The possibilities of disastrous effects upon native invertebrates, fish and waterfowl following the elimination of aquatic vegetation were emphasized by Courtney and Robins (282). Other potential hazards mentioned by these authors include dangers to rice, a threat to the Everglades kite (an endangered bird), and the introduction of an exotic protozoan found in Missouri known to be carried by the amur. A tapeworm introduced along with the amur has become a serious problem in Europe (Bardach, cited in 282).

In Britain widespread introduction was discouraged by the government in 1968 in view of possible dangers of disturbing the balance between plants and native fish (252). Five years later caution was also urged in the United States by Greenfield (181) who emphasized that the potential danger of the amur established still exists.

Early concern over the feeding habits of amur and the possibility of natural spawning led to the Conference of Exotic Fishes and Related Problems in Washington, D.C., 1968. This group recommended against further releases of the amur into the open waters of North America until it has been studied in more detail (283, 284). The Soil Conservation Service has emphasized the danger of introducing exotic species and has opposed the introduction of the amur because it might interfere with rice culture and waterfowl management (285, 286). Thirty-five states are now reported to have prohibited the importation and release of the amur (287). The decision by only a few to import amur into the United States in 1963 was emphasized as one which may affect the country for decades or centuries to come (288).

Research needs--Much of the early work on the amur was based on short term quasi-scientific, uncontrolled observations (289). The need for thorough study was emphasized by Stevenson (231). Others have advocated the need to develop good information on the effect of competition with native fish, optimum stocking rates of different size fish, the probability of spreading of new diseases, establishment of the amur in natural waters, effect upon waterfowl habitat and other organisms, effect of egested and excreted material and determination of control effectiveness of the weeds in question (268, 272, 290).

Tilapia--

Tilapia are often used to control aquatic vegetation in artificial lakes and ponds created primarily for aesthetic values (291), and attempts to utilize these fish for aquatic vascular plant control throughout the warmer regions of the world have had varying degrees of success.

Tilapia mossambica consumes some vascular plants incidental to its grazing of attached algae; these include common duckweed (*Lemna minor*), azolla (*Azolla*), cambomba (*Cambomba carolinana*), parrot feather, curly leaf pond weed (*Potamogeton crispus*), vallisneria, and southern naiad. These fish do not utilize water hyacinth but can eliminate it by destroying roots and stems (35). Studies on its feeding and growth have been conducted in Alabama (292). St. Amant and Stevens (293) prepared a bibliography of 213 selected references on this tilapia.

T. *melanopleura* prefers macrophytes to algae after it develops beyond the fry stage (294). In Rhodesia, it consumes 64 percent higher plants and 19 percent cladocerans and chironomids (34). *T. zillii* in Egypt also feeds upon both plant and animal material (295). Macrophyte density has decreased with no apparent effect upon the native fish in some southern California irrigation canals where *T. zillii* has been introduced (296, 297, 298). This species, in addition to *T. melanopleura*, is important in control of soft vegetation in Kenya (299). *T. melanopleura* has also been reported as a more efficient weed control agent than either the Java tilapia or the Nile tilapia, *T. nilotica* (61). Reservoirs in Puerto Rico have been stocked with tilapia in an attempt to control aquatic weeds (300).

The inability of tilapia to survive temperatures below 7.5-10 C in California is believed to be an effective barrier to their distribution; they would have to be restocked annually to become effective controls (297, 301). Weed control may be ineffective unless tilapia are stocked in substantial numbers (291) and stocking rates in ponds have ranged from 2,470 to 6,765 fish/ha (40, 61, 302).

Although *T. melanopleura* effectively controls some aquatic plants, its use in Florida was considered potentially harmful because of its competitiveness and reproductive potential (46). Phillippy (149) reported that it can live in 100 percent sea water, although adults refused food at concentrations higher than 66 percent. He emphasized that since the fish can adapt to sea water, it has the potential to migrate from one Florida watershed to another through the Atlantic Ocean or Gulf of Mexico and perhaps establish itself to the detriment of native fishes. It has also been reported as a menace to all vegetation and small fish in various Rhodesian water bodies (303) and may devour rice seedlings if stocked in irrigation canals (36).

T. zillii also consumes sprouting rice (296) and so should be used with caution in irrigation canals (36). *T. randalli randalli*, a prolific breeder with destructive weed eating habits, was considered potentially harmful to desirable vegetation in Lake Kariba, Rhodesia (304). Tilapia may also have had a detrimental effect upon other members of the aquatic community in Lake McIlwaine, Rhodesia, in spite of its success in weed control (van der Lingen and others, cited in 17). It was abandoned in weed control projects in the Sudan (146) and by the U.S. Bureau of Sport Fisheries and Wildlife because of disappointing results (60).

The ability of tilapia to reproduce rapidly in waters free of any natural enemies was demonstrated in an 8 ha pond containing over 30 species of plants and 19 species of frogs; plants and animals were virtually eliminated two years after the introduction of 20 *T. mossambica* and 20 *T. melanopleura* (305). The dangers of introducing species with destructive potential has been demonstrated by *T. aurea*. Courtenay *et al*. (306) and Courtenay and Robins (282) have described how this species has spread throughout central and western Florida, after its introduction as a test organism, competing with the native fish. It now dominates the fauna in many eutrophic Florida lakes (307). The tolerant characteristics of tilapia have also allowed them to colonize relatively inhospitable habitats in Africa subject to extremes of temperature, salinity and pH (308, 309).

Common and Israeli Carp--

The ability of the common carp to completely eliminate vegetation by uprooting with a subsequent increase of light limiting turbidity was recognized at an early date (310, 311, 312, 313). Although the carp is highly adapted to feed upon benthic fauna (314) it is reported to selectively consume or destroy sago pondweed, (*Potamogeton pectinatus*), coontail, elodea and pickerel weed in that order (315).

Submersed vegetation in some Alabama ponds was controlled with 400 common carp/ha (39). A carp density of 448 kg/ha was excessively destructive to submersed vegetation in some Lake Erie marsh enclosures (316). It is used for weed control in Poland (317) and is planned for introduction into Sudan to both control weeds and provide a badly needed source of animal protein (196).

Lamarra (318) found that carp could regenerate phosphorus from the sediments as a result of digestion, and suggested that a carp population of 200 kg/ha could internally load a lake with orthophosphate at 0.52 mg P/m^2/day. This phosphorus regeneration which might result in increased phytoplankton growth should be considered if bottom feeding fish such as carp are proposed for aquatic plant control.

Israeli carp (the Israel strain of the common carp) controlled certain rooted aquatics in Arkansas when stocked at the rate of 124 0.23 kg fish/ha (60). It also controlled coontail and elodea in a 1,215 ha Arkansas reservoir when about 9,980 kg of fish were stocked over 3 years (319).

Others--

Silver dollar fish (Metynnis roosevelti and Mylossoma argentum), native to South America, showed some potential in submersed plant control in California by readily grazing upon a variety of pondweeds. Grazing was much reduced below 21 C and death occurred below 15.6 C, hence utilization in temperate regions would necessitate holding the fish overwinter in warm water (320).

The gouramy (Osphronemus gorami) has been considered useful in controlling some submerged macrophytes in Asian ponds and reservoirs, but it is not as effective as tilapia (253). The tawes, (Puntius javicans) effective in weed control experiments in East Pakistan (165), is utilized in Indonesia and a few south Asian countries for the dual purpose of fish production and weed control (253).

Although the channel catfish consumes higher plants, it, along with the goldfish (Carassius auratus) is considered to have little potential for controlling aquatic weeds (40, 61).

Fowl

Domestic ducks can remove small amounts of vegetation and can be effective in floating weed control (14, 321) but human predation limits their usefulness (37). They have been used in aquatic weed control experiments in East Pakistan (165) and have been recommended in Asian countries where other suitable biological control agents are not available (253).

Muscovy ducks (Cairina moschata), stocked at 25/ha, have controlled duckweed in some Louisiana ponds (322). In Georgia, 15/ha required 2 to 11 months to achieve complete reduction on 0.3 to 0.4 ha ponds (58). These ducks were also considered to be potentially useful as biological controls in Guyana (73).

Semi-wild mallard ducks (Anas platyrhynchos) kept dairy drain lagoons free of aquatic grasses; natural breeding was sufficient to maintain the duck populations (323).

Domestic geese can be effective in clearing small ponds of duckweed (14) and have been sucessful in Hawaii in controlling aquatic grasses after efforts at physical and chemical control failed (324). While geese were considered potentially useful in Guyana, they were a threat to rice fields (73).

Swan, unlike geese, spend most of their time in the water. They consume duckweed, filamentous algae and submerged aquatics, and can prevent establishment of cattails. They have been used in some small city water reservoirs to control excessive plant growth (Van Deusen, pers. comm.). One pair of swan per 0.2-0.4 ha of pond surface represents a possible practical solution to excessive plant growth in suitable situations (72, 325, 326). The possible excessive nutrient loading of the water by waterfowl must be considered.

Mammals

Nutria--

The nutria (Myocaster coypu) has been introduced in the Near East to control narrow leaf cattail (Typha angustata), reeds (Phragmites communis) and smartweed in ponds (57). It has been recommended on an experimental scale in southeast Asia (253), and has cleared reedbeds in Britain (327). In Cameroon, Africa, 30 young nutria completely cleared a 0.53 ha pond overgrown with water grass (Eichinochla) in 14 months (299). Nutria breeding in carp ponds can significantly increase fish production by destroying the emergent vegetation (328).

Ehrlich (329) studied a series of ponds in Poland and Israel in which nutria had depleted bulrush, reeds and cattails. One pond of 8 ha was stocked with over 500 nutria in the autumn; emergent plant growth had disappeared by the following summer. The coarse vegetation was shredded and became available for further disintegration by carp, aquatic invertebrates and other forms.

The development of a Polish bog lake was reversed with nutria (330). A fenced area of 130 ha with only 2-3 ha of free water surface was stocked with 200-750 nutria per year from 1956 to 1960. The animals were completely removed by trapping during the winter. The reeds were depleted and by 1959 over 11 ha of the area was clear. Depth gradually increased and the catch of fish increased significantly. Wind, flow, and local biological factors had previously been unable to prevent filling of the lake basin; the scouring action and destruction of the vegetation by the nutria, however, established a balance between filling and emptying of the basin.

While the harvestable pelt and meat of the nutria may represent a potential source of income to developing countries (57, 253, 299), the low value of the pelt and the animals' destructive burrowing and omnivorous feeding habits mitigate against its use (73).

Manatee--

The manatee, Trichechus manatus, a voracious totally herbivorous aquatic mammal, may be a benefit in the tropics where food production is often hampered by aquatic weed infestations which impede irrigation, drainage and navigation (331). It is known to consume 36 genera of macrophytes from Florida and Guyana (73). Water hyacinth is generally not consumed when other plants are available (332).

These unique animals, which can attain a length of over 3 m and a weight of 900 kg (333, 334, 335,), can consume over one-quarter of their body weight in aquatic plants per day (73). In Guyana, two manatees cleared a canal 6.7 m wide and 1,463 m long, of aquatic weeds in 17 weeks (336). Five Florida manatees, total weight 2,268 kg, were estimated capable of clearing a 805 m canal in 3 weeks (Sguros, cited in 96). Various ponds and canals in Guyana have been kept clear of aquatic weeds for many years (335) and more than 120 manatees have been introduced into the canals of that country (73).

The use of the manatee is limited because of its susceptibility to predators, including man, and a lack of knowledge of its reproduction and physiology (14, 337, 338). If satisfactory husbandry could be achieved however, this animal could be effective in many tropical areas of the world (73). It is more effective and longer lasting in certain areas than chemical controls (336), represents a rapid and economical method of weed control, (96) and is useful in keeping channels clear (339).

The manatee does not breed in captivity and its slow reproductive rate is an obstacle to large scale utilization (73, 333). In Panamanian lagoons, selective feeding did not include the weeds used for breeding by pest insects (340). Weed control by the manatee was also tried in the Chagres River in Panama for 3 or 4 years before it was given up as unsuccessful (341).

The need for fundamental research on the reproduction, physiology and husbandry of the manatee has been urged by many (96, 331, 335, 339). The establishment of an international center for manatee research, probably in Guyana, has been recommended by scientists from eight countries. The center would study basic manatee biology, its effectiveness in weed control, and ways to promote its conservation and domestication (331, 342).

Domesticated Animals--

Controlled grazing by cattle has been suggested to control vegetation along lake shores and canal banks (Levett, cited in 14) and to prevent the spread of the vegetative mat of water hyacinth in Guyana (73). Water hyacinths, when accessible, are also eaten by cattle in Australia (343) and the Nile Valley (344). Common cattails have been controlled by grazing (345). Control of reeds by cattle can be efficient (327), but it is effective for only a short time (65). Sheep, goats and horses are less efficient than cattle in controlling reeds (327).

Water buffalo, suggested as a control for emergent vegetation in Guyana (73), may be used in an attempt to control water hyacinth near Orlando, Florida (346), and are being tested for effectiveness near Gainesville, Florida (347). An attempt to import the hippopotamus into this country for weed control has been reported; however, the animals would have been unable to withstand winter temperatures (348). Contributions of these animals to the nutrient loading of the water should be considered in any proposed control program.

CONTROL OF INSECTS

Nuisance insect emergences can be a part of eutrophic systems and biological means are one approach to their control. Most efforts have concerned mosquitoes (349, 350). Amur have been proposed for mosquito control in Russia since they will consume plants upon which the insects depend (351). Tilapia have also been considered for mosquito control, as well as for control of chironomid midge larvae (301, 352, 353).

Nuisance outbreaks of chironomid midges have been effectively reduced in limited situations by carp and goldfish stocked at 168-562 kg/ha. As their control efficiency is usually inversely proportional to the area of midge production, they are less valuable for control in large lakes (354). The leech, Helobdella stagnalis, plays a significant role in the population dynamics of a chironomid midge in a Wisconsin lake (355) and may merit further investigation.

Mississippi silversides were introduced into Clear Lake, California, to help control the "gnat", Chaoborus astictopus (62, 63, 356). However, it apparently has had little impact. (R. Brown, pers. comm.).

CONTROL OF FISH

The control of undesirable fish in eutrophic lakes through stocking of predator species is a way to establish more desirable and valuable fish populations (17). Predatory fish have long been stocked to control other species (357) and forage fish are often introduced to increase production of large piscivorous species (358). Beard (359) presented a literature review on the population dynamics, environmental and biological influences, life histories and current management techniques on predator stocking to control panfish. An annotated bibliography on bluegill stocking was compiled by Graham (360).

Predator stocking to control panfish is rarely effective (359, 361, Klingbeil and Snow, cited in 362). Stocking of walleyes (Stizostedion vitreum) to control panfish populations in a number of Wisconsin lakes was ineffective (363); in general, most walleye stocking attempts have failed, perhaps related to a lack of suitable spawning requirements (364). Bluegills (Lepomis macrochirus) in some Alabama ponds were not controlled by spotted gar (Lepisosteous oculatus) (365) nor by largemouth bass (Micropterus salmoides) in an Ohio lake (366). A variety of management procedures including heavy stocking of forage fish, heavy stocking of predators and no stocking at all failed to produce changes in fish populations in an Ohio lake (367).

Some instances of successful stocking have been reported. Young muskellunge (Esox masquinongy) placed into two Wisconsin lakes to control perch (Perca flavescens) and bass nearly eliminated the perch within a year;

however, the bass increased significantly (368). White bass (Roccus chrysops) heavily consume gizzard shad and threadfin shad (Dorosoma petenese) in open waters (369). Northern pike (Esox lucius) and bluegills were concluded to be a good stocking combination in Nebraska farm ponds (370). Northern pike stocked at the rate of 62 15 cm fish/ha or 124 5 cm fish/ha were recommended to control overabundant panfish in Colorado reservoirs (371).

Northcote (358) considered fish stocking as a science archaic in terms of numbers, size and proper timing of introduction of fish into any particular lake. Restriction of the practice to new and reclaimed lakes and to the introduction of a desirable species not already present has been recommended (Kinney, cited in 372). According to Dunst et al. (17), a successful predator stocking program must consider food preference, the size of the prey, the size of the target population and the availability of the prey.

Fish have many predators in addition to other fish, such as bullfrogs, turtles, mudpuppies, snakes, birds, mink and otter; early stages are also preyed upon by copepods, hydra, crayfish and insects (373, 374). Since some of these predators may require control to protect native fish populations (373), their introduction may also serve to control undesirable fish populations.

Dunst et al. (17) emphasized that the practice of introducing various species which serve as fish food has not been evaluated from the standpoint of lake restoration and needs further study. For instance, freshwater shrimp (Mysis relicta) have been introduced into Kootenay Lake, British Columbia, to augment the food supply of rainbow trout (Salmo gairdneri) (358), and bulk quantities of mysids have similarly been introduced into a Russian reservoir to develop a food supply for young "pike perch" (359).

SECTION 5

USE OF PATHOGENS

Plant pathogens may ultimately be one of the most important methods of controlling aquatic weeds (376). Freeman et al. (377) and Freeman and Zettler (378) have pointed out that the large number of existing plant diseases make it likely that a usable pathogen can be isolated; many plant pathogens are host specific; pathogens are in general, readily disseminated and may not require reapplication; they would not completely eliminate a plant species; and they may not be harmful to animal life. Much of the work on plant pathogens in this country is now carried out at the University of Florida, Department of Plant Pathology. Major emphasis is on identifying and evaluating diseases of the water hyacinth (*Eichhornia crassipes*), alligator weed (*Alternanthera philoxeroides*), hydrilla (*Hydrilla verticillata*) and Eurasian watermilfoil (*Myriophyllum spicatum*) (377).

VIRUSES

Control of Blue-green Algae

Cyanophages, or viruses infecting blue-green algae, were first isolated in 1963 (379). Many cyanophages have since been discovered (Table 2). A particular virus is designated by the first letter of the generic names of the algae it infects. Cyanophages resemble bacteriophages in morphology, multiplication and composition. They directly affect the photosynthetic apparatus of the host cell (397). Cyanophages are widely distributed in fresh water, having been isolated from streams, rivers, ponds, lakes, waste treatment ponds and industrial storage waters (398, 399, 400).

Jackson and Sladecek (401) reviewed progress in blue-green algal virus research from 1963-1970. The host range, morphology, chemistry, physical properties, infection process and ecology were then reviewed by Brown (402). Safferman (403) emphasized the taxonomy, history, algal control aspects and interaction of various cyanophages. Padan and Shilo (399) reviewed and discussed the characteristics, growth cycles, interactions and genetics of cyanophages. Cannon (404) and Cannon et al. (405) have discussed recent blue-green algal virus research. Safferman and Morris (406) recently compiled a bibliography containing 75 references on cyanophages and 13 references on virus-like agents infecting algae other than blue-greens.

TABLE 2. BLUE-GREEN ALGAL VIRUSES*

Virus	Host Algae	Reference	Virus	Host Algae	Reference
A-1	Anabaena variablis	380	LPP-1†	Lyngbya Plectonema Phormidium	379
A-4(L)	Anabaena variabilis	381	LPP-2	Lyngbya Plectonema Phormidium	388
AC-1	Anacystis nidulans Chroococcus minor	382	LPP-1G	Plectonema	389
AP-1	Aphanizomenon flos-aquae	383	N-1	Nostoc muscorum	390
AR-1	Anabaenopsis raciborskii Anabaenopsis circularis Raphidiopsis indica	384	S-1	Synechococcus strain NRC-1	391
AS-1	Anacystis nidulans Synechoccus cedrorum	385	SAM-1	Synechococcus cedrorum Anacystis nidulans Microcystis	392
C-1	Cylindospermum	384	SM-1	Synechococus elongatus Microcystis aeruginosa	393
D-1†	Lyngbya Plectonema Phormidium	386	Unnamed	Plectonema boryanum	394
GIII†	Lyngbya Plectonema Phormidium	387	Unnamed	Anabaena variabilis	395
			Unnamed	Microcystis aeruginosa Microcystis pulverea Microcystis musicola	396

* Modified from Dunst et al. (17) and Cannon (391), with additions.

† Probably same virus.

The interactions of blue-green algae and cyanophages are complex and depend upon fluctuations in external conditions in addition to the properties of the virus and algae. Temperature, ultra-violet radiation, and unbalanced growth conditions influence viral development which in turn may be involved in seasonal blue-green fluctuations (407). An amoeba, *Hartmanella glebae*, is also involved with the interactions of the blue-green alga *Plectonema boryanum* and LPP-1 cyanophage. There is evidence that the amoeba feeds on the alga and may serve as a reservoir for the cyanophage (405).

The degree of control that viruses might actually exercise on natural populations (403) was indicated by a case in which virus Ap-1 appeared to regulate the termination of a bloom of *Aphanizomenon flos-aquae* (383). Evidence for lysogeny, or the harboring by *Plectonema boryanum* of a cyanophage capable of causing lysis, makes natural population control more reasonable, according to Cannon et al. (408). Lysogeny induced by antibiotics, stress or pollutants may also be involved in the natural control of some blue-green algae (409, 410). Cannon (404) has suggested that the control of *Plectonema* involves a choice by the virus to kill the cell or to integrate its chromosome with that of the host.

Although cyanophages have the potential for algae control (383, 395, 397, 401, 411, 412), their practical application is still an open question (399) and further study is necessary (402). The only instance of actual control as a management procedure appears in a Russian report concerning a blue-green algal scum lysed by spray application of cyanophages (Topachevsky, cited in 413). Kraus (414, pers. comm.) believed that while cyanophage-algal relationships could indicate the eutrophic condition of the water, the resistance of blue-green algal blooms to the already present cyanophage suggests that the algae are actually scavenging the viruses from the water rather than being controlled by them. Using cyanophages to control blue-green algae in areas where there are temperate viruses (those which do not necessarily cause lysing of the host) may be impractical as the temperate virus can immunize the host against virulent forms (415). In order to prevent serious environmental consequences, Cannon (404) urged that much careful work be conducted before any attempt is made at viral regulation of natural populations.

Cannon (404) has pointed out many of the basic research needs in cyanophage research. These include understanding the chemical and biological causes of algal blooms, characterization and isolation of additional cyanophages, and study of the host-parasite relationship at its most basic level. Some recent work on cyanophages include research on a virus infecting *Anacystis nidulans* (416), screening studies on the natural waters of New Jersey for cyanophages (417), and a Nebraska study on naturally occurring viruses for algal control (418).

Control of Other Algae

Viruses in algae other than blue-greens are probably not uncommon; whether they can be utilized for control purposes remains questionable. Virus-like inclusions have been isolated from the green algae *Stigeoclonium*, Uronema, Coleochaete, and Radiofilum (419). Viruses lysing Chlorella pyrenoidosa have been reported (420, 421) and a possible virus infection has been studied in Oedogonium (422). The red alga Sirodotia tenuissima has an associated virus (423).

Control of Macrophytes

Little research has been carried out on viruses as potential biological controls of aquatic vascular plants. A virus stunting disease of alligator weed (424) has not been effective when allowed to transmit naturally (425). However, virus stunt may have some potential in controlling water hyacinth (426). A virus may have been responsible for a 95 percent decline in Eurasian watermilfoil in Cheasapeake Bay from 1965 to 1967 (427, 428). In the early 1970's, however, while watermilfoil continued to show disease symptoms, presence of a virus could not be demonstrated; hence final results were inconclusive (Southwick, pers. comm.).

BACTERIA

Control of Blue-green Algae

The relationships of blue-green algae and bacteria have been reviewed by Whitton (429). He pointed out that although the addition of bacteria which produce antagonistic substances is frequently suggested for controlling nuisance algae, such bacteria are already widespread in nature. As with viruses and other biological controls, however, the use of bacteria as potential control agents would have the advantage of eliminating the need for chemical algicides; the closer physiological and evolutionary relationships of bacteria and blue-green algae are also part of the rationale for proposing them as controls (430).

Bdellovibrio bacteriovorus is an endoparasitic bacterium under study (430) with the potential for large-scale blue-green algae control (431). Inhibition of oxygen evolution in Phormidium and Microcystis has been demonstrated (432, 433) and one B. bacteriovorus cell is capable of producing sufficient lytic factor to inhibit 75 Phormidium luridum cells (434).

Myxobacteria capable of lysing many species of blue-green algae have been isolated by Shilo (435) and Daft and Stewart (436). A bacterium which inhibited the growth of Nostoc sphaericum was isolated in Germany (437). Lysis of vegetative blue-green algae cells occurred within 30 minutes after the attachment of a bacterium isolated by Daft and Stewart (438). Bacteria which can lyse green algae have also been isolated (439, 440). Wood (418) has designed studies to find and test naturally occurring bacteria that may be effective as biological controls. The role of bacteria in the disappearance of blue-green algae blooms and the feasibility of their use is also being investigated by Ensign (416).

Control of Macrophytes

Research reports on bacterial diseases for potential control of aquatic macrophytes are rare. Freeman et al. (377) have not been able to isolate a bacterium capable of causing disease in the water hyacinth.

Control of Fish

The control of fish pathogens has been emphasized in fish management programs, but they have not been evaluated in terms of lake restoration (17). There are more outbreaks of bacterial diseases in fish in enriched than unenriched waters (441), a potential control situation which might be exploited. Shapiro (442) proposed using specific diseases against zooplanktivorous fish to increase zooplankton numbers for phytoplankton control.

FUNGI

Control of Phytoplankton

Fungal parasites of phytoplankton may delay or decrease the maximum size of the population; parasitism may also lower the development of one species with respect to another (443). Differences in the composition or amount of organic substances liberated by algae was suggested as a factor in the differences in susceptibility of members of an algal population to fungal infection (444). Safferman and Morris (445) determined that about 20 percent of over 500 studied actinomycetes and fungal isolates were antagonistic toward algae. A number of aquatic fungi parasitic on phytoplankton (446, 447, 448, 449) and diatoms (450, 451) have also been described.

Although a number of species of fungi have been listed as parasites of the blue-green algae *Anabaena*, *Aphanizomenon*, *Gomphosphaeria*, *Lyngbya*, *Microcystis*, and *Oscillatoria*, the possibility of their use has apparently not been explored (443, 452, 453). The association and physiological relationships between fungi and blue-greens, however, have been reviewed by Whitton (429).

Control of Macrophytes

A number of fungi have been identified as potential macrophyte controls, primarily for water hyacinth and hydrilla. So far, thirty species have been listed in a University of Florida project to survey, isolate, identify, test and catalog all fungi associated with the water hyacinth (454).

The fungus *Rhizoctonia solani*, first isolated from the anchoring hyacinth (*Eichhornia azurea*) in Panama, is highly pathogenic to the water hyacinth (378, 455). *R. solani* occurs commonly in Central America and the Caribbean, but not in the United States (456). It has been isolated also from India (377). This fungus is highly virulent (457); the disease, which causes severe blighting, proceeds optimally at 22-27 C (378). The RhEa strain of *R. solani* is particularly pathogenic to water hyacinth but extensive testing is still required (458).

Acremonium zonatum (=*Cephalosporium zonatum*) has been isolated from El Salvador, Panama, Puerto Rico, Florida, Louisiana and India. This fungus is evident as sunken lesions which enlarge and coalesce, becoming zonate with brown bands (377). The symptoms, isolation, morphology, culture and pathogenicity of this fungus have been described by Rintz (459). *A. zonatum* apparently does not retard the rapid growth of the hyacinth; however effects when applied at high concentrations are being explored (377, 459, 460). It may have greater potential when used in conjunction with the weevil, *Neochetina eichhorniae* (425, 461) and the mite, *Orthogalumna terrabrantis* (462, 463).

Alternaria eichhorniae is an Indian fungus which may have some utility as a water hyacinth control (464). Culture methods have been developed which demonstrate its pathogenicity (465); it is still under investigation (76, 462, 463). A form of *Fusarium roseum*, a weak pathogenic fungus that causes vascular browning of the water hyacinth was isolated in Florida (457, 466). It may not be of value unless it is augmented by some additional control method (377).

The rust *Uredo eichhorniae* attacks the water hyacinth in Argentina and has encouraging possibilities as a control in this country (425). *Helminthosporium stenospilum* is also highly destructive to the hyacinth; however, this fungus is a sugar cane parasite in some areas and its use may be restricted (425).

Fungi pathogenic to hydrilla in India are currently being studied at the University of Florida (467, 468). In addition, species of *Penicillium*, *Aspergillus* and *Trichoderma* associated with diseased hydrilla produce toxins, including oxalic acid. While the use of purified fungal toxins would have advantages over handling live pathogens, the extreme toxicity of purified fungal oxalate may preclude its use in hydrilla control (469). The RhEa strain of *Rhizoctonia solani* only occasionally infects hydrilla (458).

Fungi attacking other aquatic macrophytes have received less attention. Hayslip and Zettler (470) reviewed the past and current research on Eurasian watermilfoil; in tests they obtained only limited success with fungi reported as pathogens on other plants. The control potential of a species of *Alternaria* isolated from alligator weed in Puerto Rico is being studied (461). *Salvinia auriculata* may be controllable by a parasitic fungus (471) and although the RhEa strain of *R. solani* is strongly pathogenic to water lettuce (*Pistia stratiotes*), further work is needed to insure that it will not infect desirable species (458).

SECTION 6

BIOMANIPULATION

Considerable emphasis on biological control in the aquatic environment has been on the use of predators, grazers, or pathogens to control undesirable species. Little effort has been directed toward exploiting the interrelationships among the plants and animals and their environment to alleviate symptoms of excessive production. Patten (472) emphasized that small or inexpensive, well chosen, and correctly timed manipulations of ecosystem parameters might produce dramatic improvements in water quality. Similarly, Shapiro et al. (27) stressed the need to treat lakes as ecosystems rather than focusing entirely on controlling nutrient input.

GRAZING

Zooplankton

Phytoplankton density often depends upon nutrient concentration and zooplankton grazing. The latter in turn often depend upon phytoplankton density. These relationships were studied by O'Brien and DeNoyelles (473) who emphasized that such a system can only exist where zooplankton are not rigorously limited by predation. Manipulation of these relationships thus affords the possibility of lowering phytoplankton abundance to more desirable levels by increasing the abundance of zooplankton.

Shapiro et al. (27) suggested that the deliberate stocking of large herbivorous zooplankters such as Daphnia magna could control larger colonial algae after reduction of zooplanktivores by carnivores. This technique was felt to be of little benefit, however, where inedible phytoplankton species were present. Algae populations in such cases might then be manipulated by other means to favor production of those preferred by grazing zooplankton. They also proposed investigation of pantothenic acid additions to lakes to increase zooplankton populations but felt the economics of the treatment would probably be prohibitive.

Other applicable research in progress on grazing concerns its importance as an algal controlling factor in prairie lakes (474), and a mathematical simulation model to explore ways to reduce algal standing crops by diverting primary productivity into consumer food chains (475).

Tadpoles

Tadpoles can be a major factor in the spring reduction in the standing crop of attached filamentous green algae in small lakes. They may trigger an annual succession with widespread consequences, since factors which affect the periphyton community of a small lake may affect its entire energy budget (476). By overgrazing, they can also depress primary productivity and alter community metabolism, in addition to decreasing the relative volume of blue-green algae (477). Wassersug (478) documented the transport of nutrients from the aquatic to the terrestrial environment by frogs and toads and concluded that these organisms were important in the removal of nutrients from aquatic systems. Results of current studies on the role of tadpoles in the regulation of algal productivity will be used to model their impact on various physico-chemical components of the aquatic community (479). The relationships of tadpoles and their environment may thus suggest potential biomanipulative schemes to attain more desirable aquatic communities. Since they are preyed upon heavily by fish, tadpoles probably would not be an important control factor in large lakes.

FISH STOCKING

Reducing algal populations by stimulating increases in algae-feeding fish has been recommended as a means of long-term eutrophication control in established reservoirs (480). The somewhat different approach of introducing carnivorous fish to prey upon zooplanktivorous fish was suggested by Shapiro et al. (27). This induces an increase in grazing zooplankton able to reduce phytoplankton populations. He demonstrated this concept in pilot scale enclosures and ponds, and has now proceeded to full scale experimentation in several Minnesota lakes (481, 482).

FISH STERILIZATION AND HYBRIDIZATION

Sterilization and sex reversal in fish have been used in fish culture, and may have application in the control or manipulation of undesirable species in eutrophic systems. Sterilization, believed to have only limited promise as a biological control measure (369), may be induced by hormone injection or hybridization (193). Blue-gills (Lepomis macrochirus) have been sterilized by sub-lethal doses of gamma radiation (1000 R) in experiments on population control (483). Male fertility in guppies (Lebistes reticulatus) was adversely affected by TEPA [tris (1-aziridinyl) phosphine oxide], an insect chemosterilant (484). Use of methyltestosterone to produce sex reversal and resultant monosex populations of bluegills was generally unsuccessful (485).

Fish hybridization is an important aspect of fish culture (486, 487, 488) since the process can combine the desirable attributes of the parent stock and may result in a fish with superior qualities (193). This technique however, has had limited application in biological control programs. Sterile or monosex hybrids would have advantages over stocking fertile fish when reproduction is not desired (489). For instance, research is being conducted on developing sterile hybrids of Tilapia to control macrophytes (490). Hybridization might also be useful in biological control situations where improved predation is desirable. For example a white bass (Roccus chrysops)-

striped bass (Roccus saxatilus) hybrid was developed to produce an effective predator and control of the gizzard shad (Dorosoma cepedianum) (491, 492).

FERTILIZATION

Artificial fertilization to induce shading by phytoplankton has long been reported as an effective control of aquatic macrophytes (493, 494, 495, 496). The increased phytoplankton growths and subsequent decrease in transparency may be sufficiently objectionable, however, to preclude this as an acceptable practice. Recent evaluations of fertilization as a method of controlling higher aquatic plants in farm ponds and small lakes in Michigan have been undertaken by McNabb (497).

Fertilization with phosphate only has been satisfactory to maintain control in many ponds (498). In some instances, superphosphates and mixed commercial fertilizers reportedly caused blue-green algal blooms that resulted in fish mortalities (499). For effective control, some ponds require an average of 900-1,345 kg/ha or as much as 1,680 kg/ha each year of a fertilizer such as 8-8-2 (N, P, K) (500).

Macrophytes were eliminated in an artificial 18 ha lake in New Jersey after fertilization. Generally, 56 kg/ha of 5-10-5 inorganic fertilizer was applied seven separate times the first year; the dosage was reduced by one-half the following year using the same schedule (501, 502, 503). Similarly, application of a fertilizer every 10-14 days in a 16 ha Kansas lake controlled aquatic vegetation in depths greater than 1.5 m. Control was achieved with a total of 347 kg/ha of ammonium sulfate (21-0-0) and 226 kg/ha of triple superphosphate (0-46-0) (504).

Fertilization as a control practice yields variable results (505) and may be responsible for winter and summer kills of fish (359). Fertilizers are too expensive in some areas of southeast Asia for this method to be practical; however, macrophytes have been controlled there in ponds fertilized with sewage (253). In Pakistan, fertilization effectively prevented the regeneration of macrophytes after their removal by hand (165). Some ecological effects of shading were demonstrated in Lake Apopka, Florida (506). Gizzard shad increased in this lake after persistant phytoplankton blooms shaded out the pondweed, causing it to disappear. The shad then provided forage for an increasing gamefish population but eventually became too large and numerous, resulting in a decrease in the gamefish.

COMPETITION

Competition between aquatic plants can be utilized to eliminate or control undesirable species. Slender spikerush (Eleocharis acicularis) is competitive with certain rooted aquatic plants in California canals (507). It can progressively eliminate a variety of other plants. Its capacity for reproduction, mat-like growth form, competition for nutrients and cold-hardiness are all critical factors in its ability to out-compete other species (508, 509).

Competition has also been considered in control of Eurasian watermilfoil (Myriophyllum spicatum) by the lotus (Nelumbo lutea). Shading effects of the lotus eliminate the milfoil (510); the lotus, in turn, can be eliminated with about one-twentieth the herbicide required for milfoil (Bates and Hall, cited in 511).

ALLELOPATHY AND AUTOINHIBITION

Allelopathy, the subject of a recent review by Rice (512), refers to the growth limiting effects of higher plants upon each other through the release of retardants into the environment. Current usage also includes the direct or indirect effects of chemical compounds excreted by micro-organisms. It has also been used to describe heteroinhibition in algae or the suppressing action of one species upon another (28). These interactions may prove to be a major factor in determining the composition of plant communities (508). Autoinhibition describes the inhibition by an algal species of its own growth by the secretion of organic compounds (28, 513). The exploitation of allelopathic and autoinhibitory substances seems a promising area for research on biological control of algae.

Studies in the 1940's resulted in the isolation of a growth-inhibiting substance, chlorellin, produced by the green alga, Chlorella vulgaris (514, 515, 516). Exceedingly low concentrations of this substance stimulate the growth of Chlorella cells (517), while higher concentrations inhibit Chlorella and other algal species (518). Later work confirmed that inhibitory secretions influenced the ecology of blooms (519) and demonstrated that aquatic macrophytes appear capable of altering phytoplankton populations (520, 521). These inhibitory substances are important in competition among algal species (522) and are important in the development of the algal flora (512, 523).

Inhibitory substances produced by green algae of the Volvocaceae and their role in biological control have been studied extensively (513, 524, 525, 526, 527). A substance produced by Pandorina morum has produced encouraging results (527, 528). The manner in which these algal inhibitors operate and their effect upon other organisms are largely unknown; however, there is hope that they can be synthesized (529).

A heteroinhibitory or allelopathic compound secreted by the bluegreen alga Anabaena flos-aquae appears to be an important factor in its bloom formation; it prevents cell division and inhibits the growth of other algae in the community (530). Compounds of this nature may offer new control prospects for objectionable blue-greens. However, allelopathy was felt to be insignificant in maintaining an Aphanizomenon bloom, and autoinhibition was not a factor in a declining spring bloom of Aphanizomenon in Clear Lake, California (28).

ENVIRONMENTAL MANIPULATIONS

Shapiro et al. (27; Shapiro, cited in 482) conducted a series of experiments in which predominant algal populations were shifted from bluegreens to greens by addition of HCl, CO_2, and Cl_2. The researchers explained the shifts on the basis of competition for CO_2 or phosphate but also suggested that the blue-greens may have been stressed by these additions, thereby becoming more susceptible to cyanophages.

The importance of water circulation in algal population shifts was also emphasized by Shapiro et al. (27). The hypothesis that it can cause a shift by lowering the pH or increasing the CO_2 is being investigated (485). High pH is also lethal to some zooplankton; lowering it by increasing circulation was suggested as a possible method to increase the abundance of these grazers with a subsequent lowering of the algal populations (27).

SECTION 7

ECONOMICS OF BIOLOGICAL CONTROL

Little has been published on the cost of biological control practices. However, they are often advocated as less costly than other methods because of ease of initiation, minimum requirements for trained personnel, and general longevity of treatment (37). These considerations are important in less developed countries (165, 531).

That biological control offers an economic, as well as ecological, alternative to herbicides was demonstrated by Bates (185) who compared the costs between use of the amur and chemical treatment in Arkansas and Alabama farm ponds. The annual cost per year for chemical control was estimated at $141/ha, whereas the annual cost per hectare over a 10 year period for biological control was estimated at $25. Aquatic weed control costs were reduced from an annual expense of $3,000-5,000 to an initial cost of only $25 after the introduction of Java tilapia at a Hawaiian sugar company (Hee, cited in 61). It was predicted that this tilapia could be produced for slightly over $1/kg in 1960 (Shefler, cited in 297).

Virtually no economic information could be found on biological control procedures using organisms other than fish. One study has indicated that the snail Marsia cornuarietis could be reared for about six cents each if 12 million a year were produced; however, this cost makes the high stocking rates necessary for control impractical in most waters (532). As biological control procedures become utilized to a greater extent and the costs of mechanical and chemical treatment continue to rise, practices considered too costly now may become acceptable.

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